Detailed Analysis of Nearby Bulgelike Dwarf Stars II. Lithium Abundances

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ABSTRACT

Li abundances are derived for a sample of bulgelike stars with isochronal ages of 10-11 Gyr. These stars have orbits with pericentric distances, R_p, as small as 2-3 kpc and $Z_{max} < 1$ kpc. The sample comprises G and K dwarf stars in the metallicity range -0.80≤[Fe/H]≤ +0.40. Few data of Li abundances in old turn-off stars (≥ 4.5 Gyr) within the present metallicity range are available. M67 (4.7 Gyr) and NGC 188 (6 Gyr) are the oldest studied metal-rich open clusters with late-type stars. Li abundances have also been studied for few samples of old metal-rich field stars. In the present work a high dispersion in Li abundances is found for bulgelike stars for all the metallicity range, comparable with values in M67. The role of metallicity and age on a Li depletion pattern is discussed. The possible connection between Li depletion and oxygen abundance due to atmospheric opacity effects is investigated.

Subject headings: stars: abundances - stars: chemical evolution - stars: late-type - elments: lithium

1. Introduction

Lithium is a key element in astrophysics. The inference of the original lithium abundance in the universe should provide the cosmic ratio of baryons to photons at primordial times, and constrain the standard model of Big Bang nucleosynthesis. Li is destroyed in stars by ^{7}Li(p,α)^{4}He reactions at T $\geq 2.5 \times 10^6$ K. On the other hand, different sources of Li, besides the primordial nucleosynthesis, have been proposed: novae, asymptotic and red giant branch stars, C-stars and Type II SNe, and spallation of C, N, O elements by galactic cosmic rays in the interestellar medium. To infer the primordial Li abundance an overall understanding of the different destruction/production mechanisms and their rates is required.

In a classical work, Spite & Spite (1982) detected an almost uniform Li abundance in halo stars. This "Li plateau", with A(Li)[1] $\sim$ 2.1, is constant for all metal-poor stars within the temperature range 5700 K $\leq T_{\rm eff} \leq$ 6300 K. Many authors consider this value as the primordial Li abundance of the protogalactic cloud. Others claim that it is depleted by about 0.2-0.3 dex from the primordial value (for recent reviews see Cayrel 1998; Spite et al. 1998; Pinsonneault et al. 2000).

Solar-system observations led to meteoritic Li abundances of A(Li) $\sim$ 3.3 (Grevesse et al. 1996). T Tauri stars provided a similar value, A(Li) $\sim$ 3.2 (Magazzú et al. 1992) and pre-MS stars in the Orion Nebula provided values of A(Li) $\sim$ 3.6 (King 1993) and A(Li) $\sim$ 3.2 (Cunha et al. 1995). These observations show that there is a roughly constant galactic interestellar medium (ISM) abundance. If the Li plateau value is the actual primordial value, the ISM abundance is enhanced by a

[1] A(Li) = log ε(Li)= log [N(Li)/N(H)] + 12

factor of ten. Therefore the understanding of the galactic Li history demands a complete theory of stellar evolution and their contribution to the ISM enrichment.

Standard models, which have successfully explained stellar evolution and HR diagrams, predict that convection is the only mechanism that rules Li depletion in low-mass stars. In these models Li depletion is a function of stellar mass, metallicity and age (e.g. D'Antona & Mazzitelli 1984; Proffitt & Michaud 1989).

Open clusters are natural targets to probe these models because they have stellar contents of high metallicity sampling an evolutionary sequence. However, their study revealed a more complex picture than that outlined by standard models. MS depletion is expected to occur only in the lower mass (M<0.9 $M_{\odot}$) stars. But observations indicate that a depletion mechanism acts during the entire MS lifetime even in stars where the temperature at the bottom of the convective zone (CZ) is not high enough to burn Li. In addition, stars with the same age, composition and mass show dispersions in A(Li) as high as 1.5 dex (e.g. Soderblom et al. 1993a for Pleiades late-G and early-K stars, and Pasquini et al. 1997 for M67).

Non-standard models with different depletion mechanisms have been suggested to account for the observations: mixing driven by angular momentum loss, microscopic diffusion, internal wave diffusion, differential rotation and depletion by MS mass loss (see Pinsonneault 1997, Deliyannis et al. 2000 and Pinsonneault et al. 2000). None of these models provided a satisfactory fit to observations alone, indicating that two or more mechanisms are acting together.

A comprehensive literature is available for lithium in open clusters. In the last two decades, several groups observed and derived Li abundances for several open clusters solar-type stars. Some examples of studied young clusters are: Blanco 1 (Jeffries 1997), α Per (Boesgaard et al. 1988; García López et al. 1994; Balachandran et al. 1996; Randich et al. 1997), Ursa Major Group (Soderblom et al. 1993b) and Pleiades (Boesgaard et al. 1988; García López et al. 1994; Soderblom et al. 1993a; Jones et al. 1996). With ages in the range 30-100 Myr, they have stars which have just arrived to the ZAMS. Therefore their abundance patterns are records of PMS depletion activity. Large spreads in Li abundance are observed in these clusters in the temperature range 5500 K $\leq T_{\rm eff} \leq$ 4500 K.

M34 (Jones et al. 1997), NGC 6475 (James et al. 1997), with 200-300 Myr and NGC 6633 (Jeffries 1997), Hyades (Thornburn, 1993, Soderblom et al. 1995) and Praesepe (Soderblom et al. 1993c) with 600-800 Myr are young clusters with stars of relatively short evolution time spent in MS. NGC 754 (Hobbs & Pilachowski 1986) and IC 4651 and NGC 3688 (Randich et al. 2000) with $\sim$ 2 Gyr are intermediate age clusters. These groups show decreasing Li abundances with age.

Few data are available for old stars in open clusters or in the field for the present metallicity (-0.80$\leq$[Fe/H]$\leq$ +0.40) and temperature (4700 K $\leq T_{\rm eff} \leq$ 5900 K) ranges. M67 (Pasquini et al. 1997; Jones et al. 1999) and NGC 188 (Hobbs & Pilachowski 1988) with ages 4.7 and 6 Gyr respectively, are the oldest open clusters with derived Li abundances. Field samples with inhomogeneous ages and kinematics were also studied (Pasquini et al. 1994; Favata et al. 1996; Chen et al. 2001). For hotter stars the behavior of A(Li) vs. temperature was studied by e.g. Lambert et al. (1991) and Boesgaard et al. (2001).

In present work we derive Li abundances for a kinematically selected sample. The stars from this sample have highly eccentric orbits indicating an inner disk or bulge origin. The sample selection and kinematical properties are described in Grenon (1999, 2000). A detailed analysis of these stars was presented in Pompéia, Barbuy & Grenon (2001, hereafter Paper I). Binaries are rejected using Hipparcos photometry and radial velocity measurements. Isochronal ages are 10-11 Gyr, making this one of the oldest samples with derived Li abundances in the studied metallicity range.

2. Observations and Analysis

The spectra were obtained in September 1999, at the 1.52m telescope of ESO, La Silla, with the FEROS spectrograph. The standard star+sky configuration was used. The spectral coverage is from 356 to 920 nm, with a R=48,000 resolution. Data reduction was performed using the ESO pipeline package for reductions of FEROS data (DRS), in MIDAS environment.

Stellar parameters are those derived in Paper I, where effective temperatures were derived using Hα profiles and surface gravities were inferred by requiring ionization equilibrium of Fe I and Fe II lines. MARCS model atmospheres (Gustafsson et al. 1975) were employed. Metallicities and microturbulent velocities were determined by using curves of growth for Fe I and Fe II. Stellar masses were derived from isochrones of Vandenberg (1985) and VandenBerg & Laskarides (1987). A detailed description of the determination of stellar parameters is presented in Paper I. In Table 1 effective temperatures, gravities, microturbulence velocities, metallicities and masses are reported.

2.1. Li Abundances

Li abundances were determined by using synthetic spectra in the region of the Li doublet at λ 6707.76 Å. The spectrum synthesis code is described in Cayrel et al. (1991). The atomic line list in the region is reproduced in Table 2 and molecular lines of TiO, C_2 and CN are included.

The λ 6103.4 Å Li line is known to be less perturbed by NLTE effects than the resonance one at λ 6707.76 Å. However due to the metallicity and atmospheric parameters range of our sample, it is heavily blended and undetectable for most of the stars. The NLTE effects for the λ 6707.76 Å doublet of our sample stars are of the order of [Li/H] $\sim$ 0.012 (Carlsson et al. 1994) and do not affect the results.

Errors in Li abundances are dominated by temperature uncertainties. The estimated error in A(Li) is 0.07 dex for a $T_{\rm eff}$ change of 100 K. The calculated Li abundances are also reported in Table 1. In Fig. 1 the Li line syntheses for HD 211706 and HD 10576 are shown.

3. Discussion

3.1. Li vs. $T_{\rm eff}$

In Fig. 2 Li abundances vs. $T_{\rm eff}$ are plotted. Most of the determined abundances for the sample stars represent upper limits indicating that the line depth is below the limit of 2σ of the noise. Nevertheless, an upper envelope of high-Li stars is also observed.

A large spread in Li abundances is present for stars with the same temperature. Large spreads in Li abundances were also inferred for other samples of turn-off field stars with different compositions and ages (Lambert et al. 1991; Pasquini et al. 1994; Favata et al. 1996; Chen et al. 2001), and even for very homogeneous samples as M67 G-type stars (Pasquini et al. 1997; Jones et al. 1999).

3.2. Li vs. age

The correlation between Li abundances and age is examined in Fig. 3 where the A(Li) vs. $T_{\rm eff}$ is plotted compared to that for M67. As shown in this figure, the two samples overlap. The lack of a depleted pattern of bulgelike relative to M67 stars suggest that Li depletion mechanisms become inefficient with age. Open clusters observations are in agreement to this suggestion. The depletion rate apparently decreases with time given that higher depletion is observed among young clusters with different ages (50 to 600 Myr) than among old clusters (1 to 4 Gyr) (Jeffries 2000). Pasquini (2000) suggested that no depletion mechanism acts for ages older than $\sim$ 1.6 Gyr. Based on a sample of field stars, Chen et al. (2001) have also claimed that Li depletion occurs early in life, at ages $\leq$ 1.5 Gyr. Our sample, with much older stars and with some high-Li, supports this suggestion.

3.3. Li vs. Mass

Standard models predict that high-mass stars preserve more of their Li than lower mass stars. In Fig. 4 we plotted the A(Li) vs. Mass ($M/M_\odot$). A slight trend of Li abundance with mass is observed although with some scatter, probably due to the action of other depletion mechanisms, such as rotation-driven mechanisms which depend on the rotation history of the star.

3.4. Li vs. [Fe/H]

The depth of the convection zone is larger for higher metallicity stars, therefore these stars are predicted to burn more their Li than lower metallicity stars with the same temperature. In order to check the role of metallicities in Li depletion we compare in Fig. 5 our Li data to that for NGC 6397 (Castilho et al. 2000), a 11.5 Gyr cluster (Chaboyer 1998) with metallicity [Fe/H] = -2.0. This figure shows that, although older, NGC 6397 stars have preserved more of their Li content than most of the bulgelike stars with the same temperature. On the other hand, some high-Li bulgelike stars are also observed.

In order to test the correlation between metallicity and the Li content we plotted A(Li) vs. [Fe/H] in Fig. 6. Different symbols represent different ranges of effective temperature. No apparent trend between Li abundance and metallicity is found for any of the temperature ranges. Nevertheless, a weak correlation with metallicity may be present contributing to the dispersion in Li abundances.

3.5. Li vs. [O/H]

Swenson et al. (1994) developed stellar models taking into account improved interior and surface opacities. They argue that elements such as Si, O, Ne and Mg may induce opacity changes, resulting in different Li burning rates. Their results pointed out that oxygen, together with iron, is the main contributor to the opacity. They estimated that an oxygen enhancement of [O/Fe] $\sim$ +0.20 could increase significantly the Li depletion rate; using new opacity tables with enhanced oxygen-to-iron ratio they reproduced the observed pattern of the Hyades stars.

In order to analyze if oxygen abundances contribute to Li depletion we compared Li abundances with the oxygen abundances derived in Paper I. In Fig. 7 A(Li) vs. [O/H] are plotted. A statistical analysis is performed and a correlation coefficient of r = - 0.23 is inferred. This coefficient indicates that essentially no dependence exists between Li and oxygen abundances.

4. Summary

In the present work lithium abundances for a sample of bulgelike stars with isochronal ages of 10-11 Gyr are reported. High-Li and low-Li stars are observed. The overlap between lithium curves for M67, a 4 Gyr open cluster, and our bulgelike sample, $\sim$ 5 Gyr older, seems to indicate that the depletion mechanisms become inefficient with age and no depletion occurs during the latter stages (ages older than $\sim$ 1.5 Gyr) of the MS.

The derived Li abundances show that a high dispersion is present for bulgelike stars with the same tempera-

ture comparable to that observed in field samples and in M67 stars. No apparent correlation between [Fe/H] and A(Li) is found, although differences in metallicities may account for part of the observed Li dispersion. A spread in the Li abundance vs. stellar mass with a possible weak trend is obtained.

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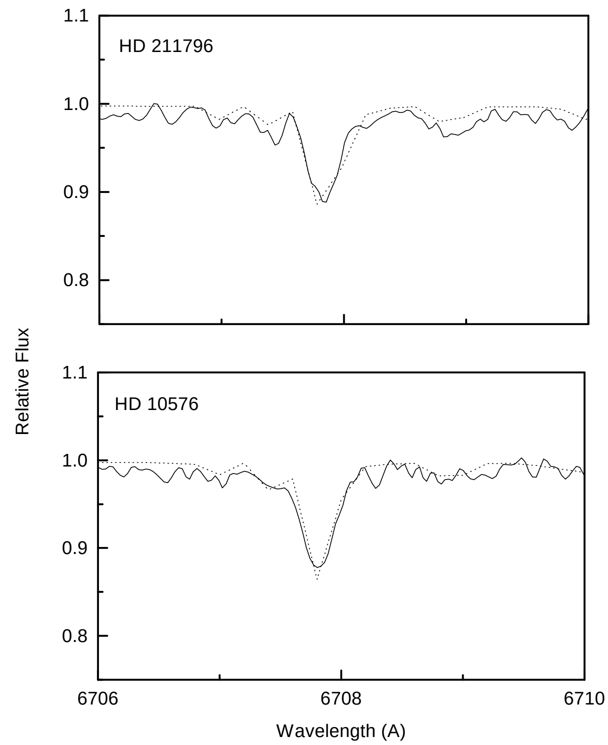

Fig. 1.— Synthetic (dashed line) and observed (solid line) spectra of HD 211706 and HD 10576.

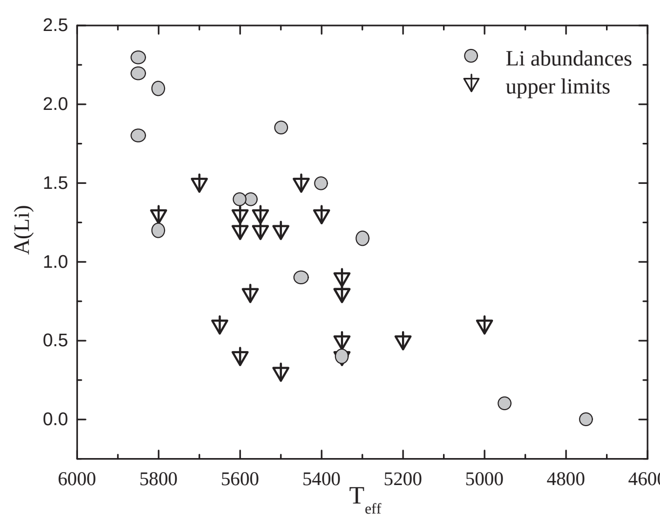

Fig. 2.— Li abundances vs. effective temperatures for the sample stars. Down triangles represent upper limits.

Table 1
Atmospheric Parameters and Lithium abundances for the sample stars

Name	T_{eff}	$M/M_{\odot}$	log g	[Fe/H]	$\xi(kms^{-1})$	A(Li)
HD 143016	5575	0.85	3.8	-0.50	1.0	< 0.8
HD 143102	5500	1.10	3.7	0.10	0.9	1.85
HD 148530	5350	0.90	4.3	0.00	0.5	< 0.4
HD 149256	5350	0.80	3.6	0.26	1.1	< 0.8
HD 152391	5300	0.90	3.9	-0.12	0.9	1.25
HDE326583	5600	1.00	3.7	-0.50	0.6	< 1.2
HD 175617	5550	0.80	4.7	-0.48	0.5	< 1.4
HD 178737	5575	0.90	4.0	-0.33	0.6	1.4
HD 179764	5450	0.90	4.2	0.05	0.5	0.7
HD 181234	5350	0.90	4.1	0.38	0.8	< 0.5
HD 184846	5600	0.85	4.0	-0.25	0.8	< 0.4
BD-176035	4750	0.85	3.8	0.05	1.0	0.0
HD 198245	5650	0.80	4.3	-0.65	0.5	< 0.6
HD 201237	4950	0.95	4.3	-0.05	0.5	0.3
HD 211276	5500	0.85	4.0	-0.55	0.5	< 1.2
HD 211532	5350	0.80	4.7	-0.70	0.5	< 0.8
HD 211706	5800	1.00	3.7	-0.05	1.0	2.1
HD 214059	5550	0.90	3.8	-0.33	0.65	< 1.3
CD-4015036	5350	0.90	4.1	-0.10	0.5	0.5
HD 219180	5400	0.80	4.4	-0.70	0.5	1.5
HD 220536	5850	0.95	3.9	-0.22	1.0	2.2
HD 220993	5600	0.90	4.0	-0.30	0.7	< 1.4
HD 224383	5800	1.00	4.1	-0.02	1.0	1.4
HD 4308	5600	0.90	4.0	-0.40	0.7	< 1.3
HD 6734	5000	1.05	3.1	-0.53	0.8	< 0.8
HD 8638	5500	0.85	4.1	-0.50	0.9	< 0.3
HD 9424	5350	0.90	4.0	0.00	0.8	< 0.9
HD 10576	5850	1.00	3.6	-0.12	1.25	2.3
HD 10785	5850	0.95	4.2	-0.25	1.0	1.9
HD 11306	5200	0.85	4.3	-0.60	0.6	< 0.6
HD 11397	5400	0.80	4.0	-0.70	0.6	< 1.5
HD 14282	5800	0.95	3.7	-0.40	1.0	< 1.3
HD 16623	5700	0.90	4.0	-0.60	1.0	< 1.5
BD-02 603	5300	0.90	3.9	-0.75	0.8	< 1.5
HD 21543	5650	0.70	4.1	-0.55	0.5	< 1.4

Table 2
The Line List and gf-values Around the Li Line

Species	λ (Å)	χ(eV)	log gf	References
Si1	6707.050	5.95	-5.00	B
Fe1	6707.441	4.68	-2.40	B
Sm2	6707.450	0.93	-1.04	L
V1	6707.563	2.74	-1.53	B
Cr1	6707.644	4.21	-2.14	B
Ce2	6707.740	0.50	-3.02	L
Li7	6707.776	0.00	0.00	S
Li7	6707.927	0.00	-0.30	S
V1	6708.100	1.22	-2.99	B
Fe1	6708.320	3.00	-4.70	B
Ti1	6708.755	3.92	-0.09	B
Fe1	6708.780	3.00	-4.39	B
Fe1	6708.955	3.00	-4.48	B

References.—(B) Barbuy et al. (1999), (L) Lambert et al. (1993), (S) Spite & Spite (1982)

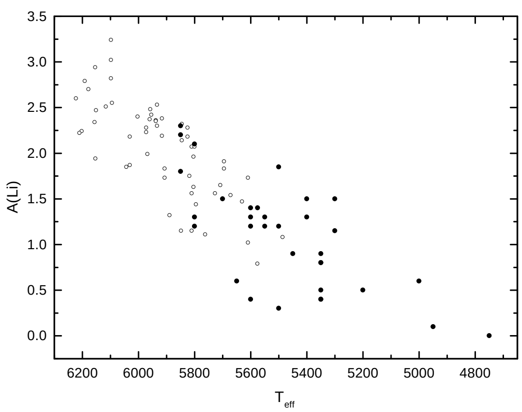

Fig. 3.— Li abundances vs. effective temperatures for our sample stars (solid circles) compared to M67 cluster stars (open circles) (Pasquini et al. 1997).

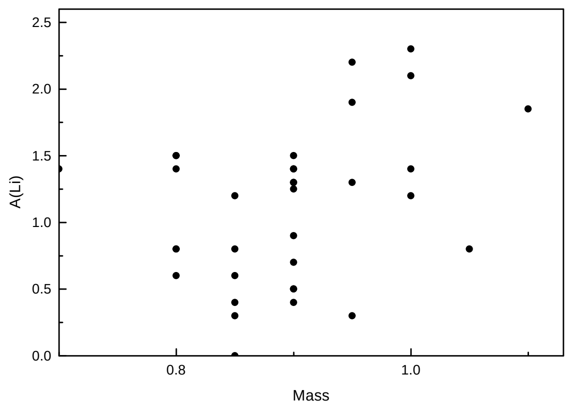

Fig. 4.— Li abundances vs. Mass ($M/M_{\odot}$).

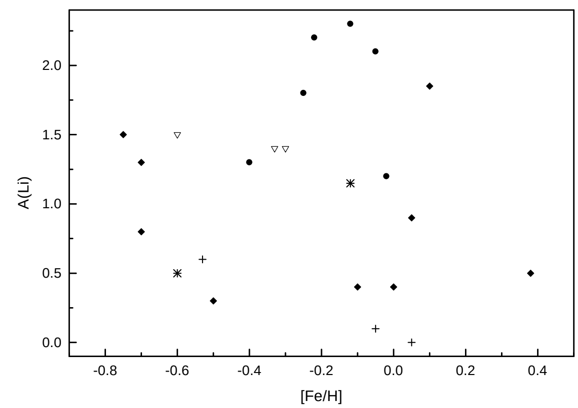

Fig. 6.— Li abundances vs. metallicity. The symbols represent different temperature ranges: 4850-5000 K (stars), 5050-5300 K (crosses), 5350-5500 K (down triangles), 5550-5700 K (diamonds), 5750-5900 K (circles)

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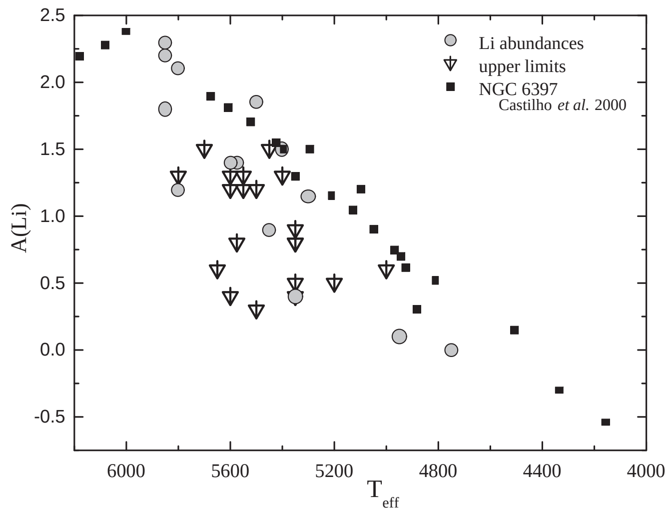

Fig. 5.— Li abundances vs. effective temperatures for our sample stars and for NGC 6397 (Castilho et al. 2000).

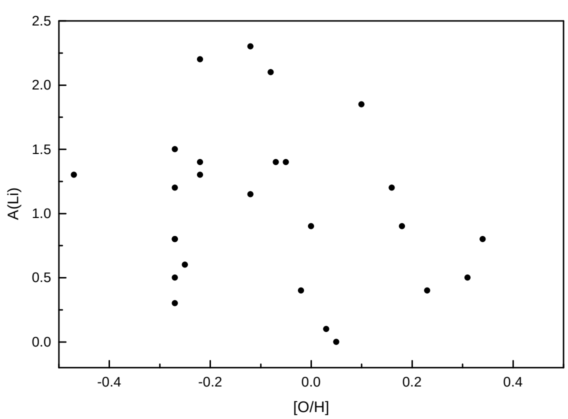

Fig. 7.— Li abundances vs. oxygen abundances.